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WILLIAM N. KLORIG

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by

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

IN

MECHANICAL ENGINEERING

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Monterey, California

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ABSTRACT

The time-thickness variation of a film of Castor Oil was determined under conditions of high intensity-short duration loading. This was accomplished through the use of a light measurement technique and a test unit designed and constructed at the United States Naval Postgraduate School. Both the method and the test unit are discussed in detail. The cases of a film between surfaces with and without relative motion were investigated. The results, in the form of oscilloscope trace photographs, show clearly indications of both plastic and elastic behavior of the film under impact loading.

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1. INTRODUCTION

The present day trend is toward higher speeds and loading for machine elements. In addition, situations, where the incompatible requirements of high performance and extreme reliability are imposed, occur with greater frequency. It is not surprising, therefore, that an understanding of the nature of lubricant action is becoming increasingly important, as lubrication plays a major role in both performance and reliability.

In machine elements such as gears, cams, ball and roller bearings, etc., the lubricant film is subjected to extreme pressures of short-duration during operation. [1, 15]*. If the lubricant film is ruptured or reduced to a thickness below the height of the surface asperities, metal to metal contact is established and wear occurs. Studies on wear, however, indicate that a continuous film is maintained, even if the reasons for this are not completely known.

Prior investigations in the field indicate the possibility of large viscosity changes under these conditions, even to the point where the lubricant acts as a plastic solid rather than as a Newtonian fluid, amenable to description by Elastohydrodynamic Theory. [4,2,3] . The rate of loading, apparently, plays an important part in this phenomena. It is also probable that the surfaces are

*Numbers in brackets refer to corresponding numbers in the Bibliography.

elastically deformed giving a band of contact (similar to the Hertzian Contact Area predicted for non-lubricated surfaces) rather than the nominal line contact.[6].

Before the mechanism of film maintenance is understood, accurate data on film properties and behavior must be compiled. [2,4,5].

It was the purpose of this investigation to determine the time-thickness history of the film in order to provide more insight into its reaction to loading. Because of the lack of precise rheological data on lubricant films under high pressure and the inherent difficulties of mechanical measurement of film thickness, a light measurement technique was employed. [4]. A collimated light beam, passed through the film, was measured by a photomultiplier and the resultant signal displayed on an oscilloscope.

Both the advantages and the shortcomings of the method are discussed.

2. TEST UNIT DESCRIPTION

DESIGN

A test unit was desired that would permit film thickness measurements while simulating the operation of a set of machine elements dependent on thin film lubrication. From those elements where such lubrication obtains, straight spur gears were selected for simulation. This choice provided the opportunity to study film behavior where a relative velocity exists between the members (contact at other than the pitch point) as well as in pure rolling (contact at the pitch point). By approximating the involute surfaces of the gears as cylindrical, a simple basic test unit could be designed to provide film loading and measurement capabilities in the operating modes described above.

As perusal of the work in this field seemed to indicate less than satisfactory results using various electrical and mechanical techniques, it was decided to try a method employing the measurement of the amount of light passed through the film separating the simulated surfaces.

The final design was to provide the capability for simulating the relative velocities of high speed gears with pitch line velocities of the order of 20,000 feet per minute, as well as that of imposing a high film loading. An electromagnetically released weight falling from various heights was felt to be the best method of achieving the desired film loading, and a DC motor drive the most suitable for the speed variation required.

To minimize the effects of test unit member deflections and externally induced vibration, the design provided for massive construction and shock mounting.

To assure a minimum of delay in fabrication and instrumentation of the unit, it was considered desirable to design as much as possible around material available in machine shop stores and instruments obtainable on a loan basis. Accessibility of test surfaces for instrument placement was an important factor in the design.

FINAL CONFIGURATION

As finally configured, the unit employs two inter-changeable sets of test surfaces shown in Figures 1 and 2. One set is provided for testing with no relative motion, the other set is powered by a 1/2HP DC motor allowing the amount of relative motion to be varied at will. The same gravity-loading, adjustment, illumination, and instrumentation systems were used for both types of testing. Each of these systems will be considered in turn.

The system for applying the impact loading to the oil film consists of a 2.88 pound weight, a drop tube and an electromagnet. The drop tube provides guidance to the weight during its fall, and a reference scale for setting the drop height. The electromagnet is used for weight positioning, release, and retrieval.

The weight is an assembly of three parts consisting of a spherical non-ferritic stainless steel striking piece, a mild steel body sized to the drop tube for guidance, and a mild steel tail which is the pole piece of the electromagnet.

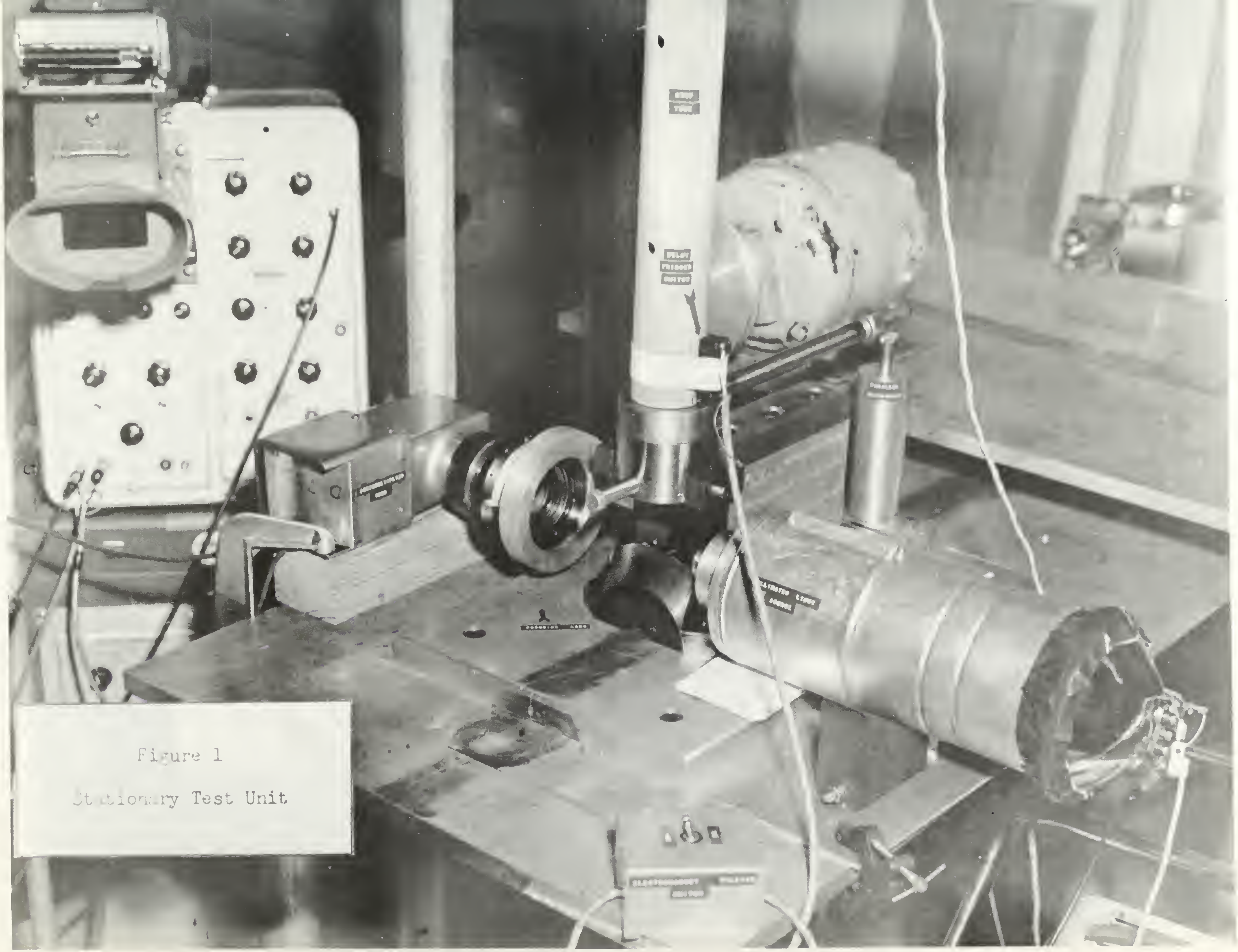


Figure 1

Stationary Test Unit

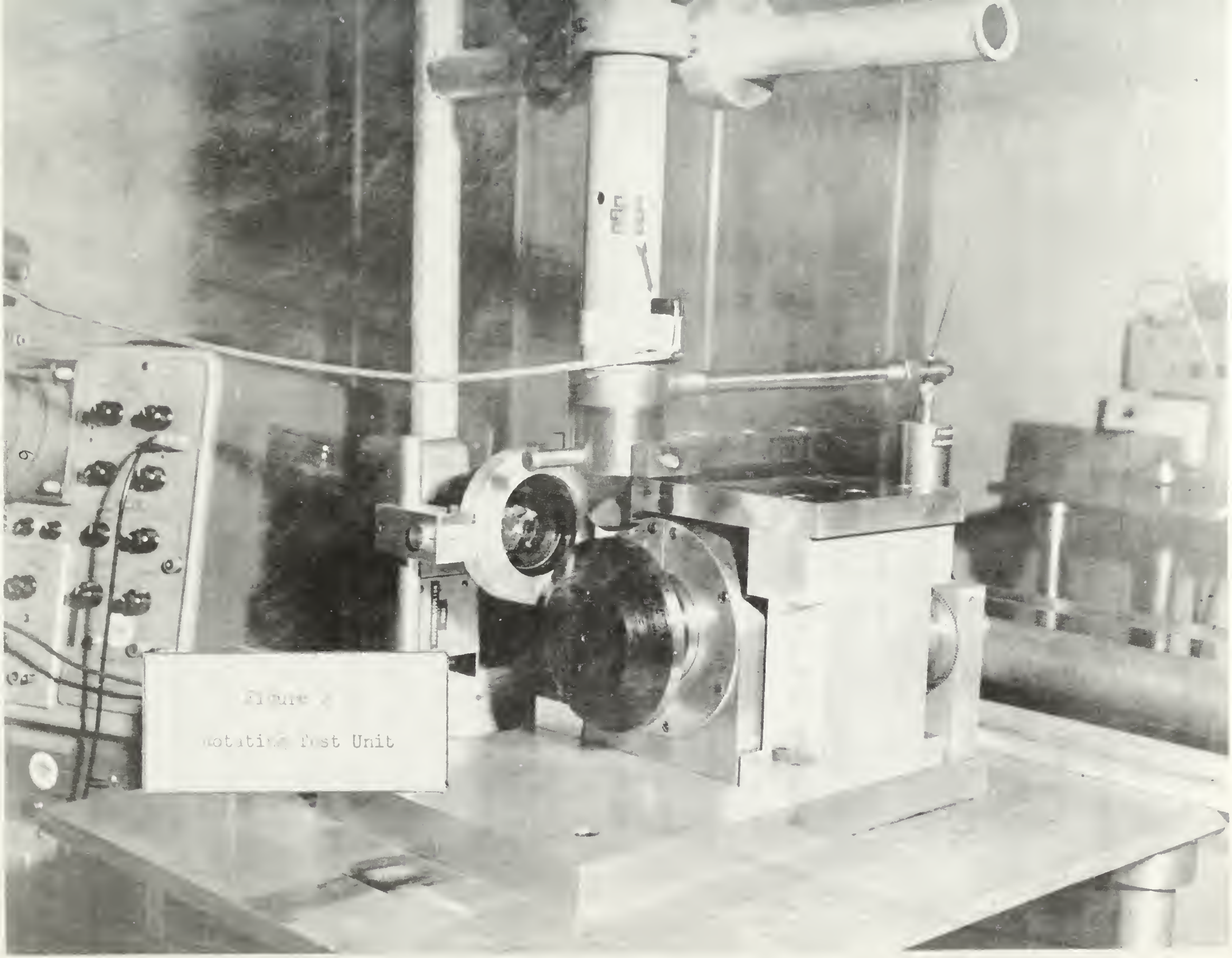


Figure
Rotating Test Unit

The drop tube had to be non-magnetic material and a 5 foot 8 inch length of 2 inch ID polyethylene pipe was used. Because of the close fit of both the electromagnet housing and the bearing surface of the weight body to the tube ID, a partial vacuum was created during the fall of the weight. This created a large braking effect on the fall. To correct this condition holes, spaced six inches apart, were drilled through the tube down its entire length. These serve the triple function of vacuum breaking, weight position observation, and with a rod inserted, a safety feature in the case of current interruption to the magnet. The drop tube is attached by aluminum hangers to a steel support stand with provisions for adjustment for alignment and plumbness. To prevent the transmission of any possible vibration set up in the tube by the action of the falling weight to the test unit, no connection was made between the two.

The electromagnet used was a surplus 24 volt aircraft starter solenoid. The magnet was found to have sufficient holding power to support and raise the weight when operated on a 6 volt automobile storage battery. The solenoid was encased in an aluminum shell, sized to the drop tube and fitted with a cord attachment eye to complete the assembly. Figure 3 is a photograph of the weight and electromagnet.

To assure that the test surfaces were parallel to one another, prior to and during testing, the adjustment system, shown in Figure 4, was incorporated. This was accomplished by trunion mounting, the movable surface guide, in such a fashion that its rotation

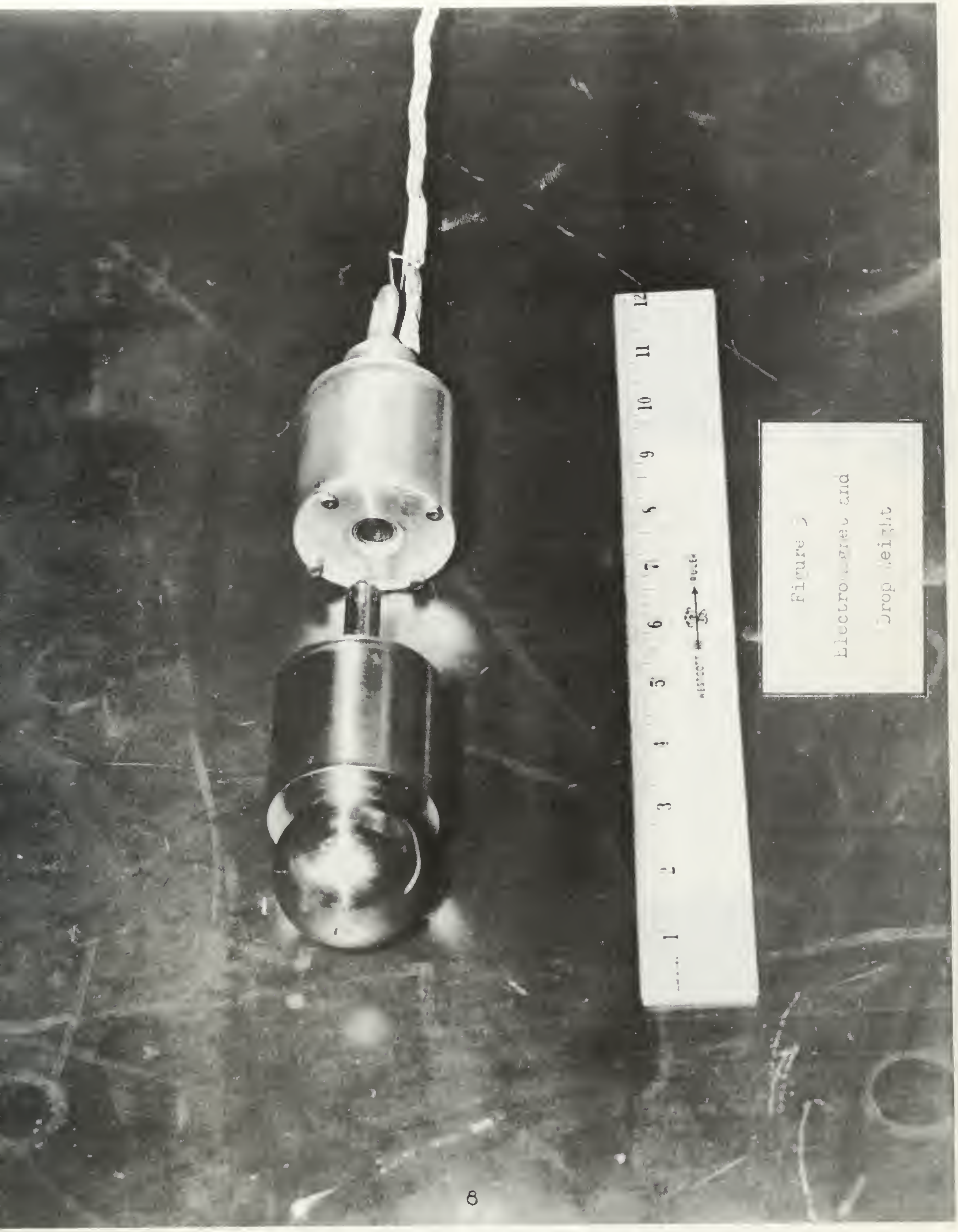
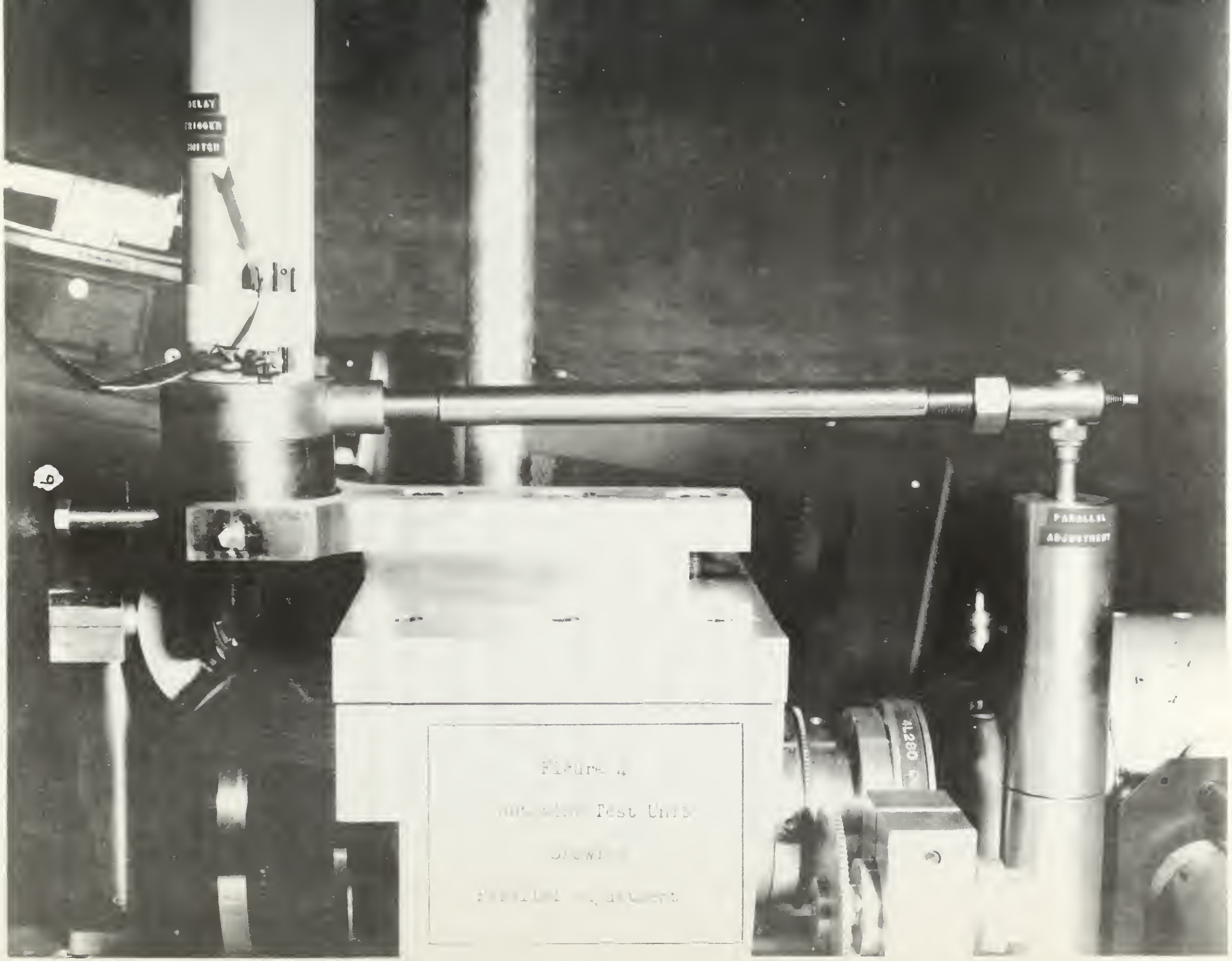


Figure 5
Electromagnet and
Drop Weight


DELAY
TRIGGER
SWITCH
PARALLEL
ADJUSTMENT
4L280
Figure 4
Test Unit

could be controlled by a lever-micrometer combination. The smallest unit adjustment of the micrometer (.0001") then caused a point on the movable surface to cover an arc length of .00001". This supporting and adjustment system was mounted on an accurately machined and rather massive foundation to assure precise alignment and negligible element deflection during testing.

The test surfaces were machined from AISI 8620 free cutting steel, and were case hardened to provide a 1/16" case and surface hardness of 50-60 Rockwell "C". All surfaces were ground to provide a 6 microinch Center Line Average finish in the direction parallel to the collimated light beam. A 7.8 microinch Center Line Average was obtained in the direction perpendicular to the light path. TALYSURF reading were taken on the test surfaces. The diagrams are shown in Figures 5 and 6. The upper or movable surface is identical for both stationary and moving surface tests. The upper body of this piece was ground and fitted to an internally ground guide collar which was then trunion mounted as described previously. A ball tensioning device was also installed in this collar to provide a method of fixing the movable member in any location desired for calibration or pre-test positioning. The other test surface is interchangeable; an arc segment for pitch point testing or a cylindrical surface on a massive shaft running in precision bearings for the relative motion testing.

The base plates for both test units are aluminum plate, machined to assure flatness and parallel surfaces. This plate is 1 inch thick for the pitch point test unit and 1.5 inches for the rotating unit.

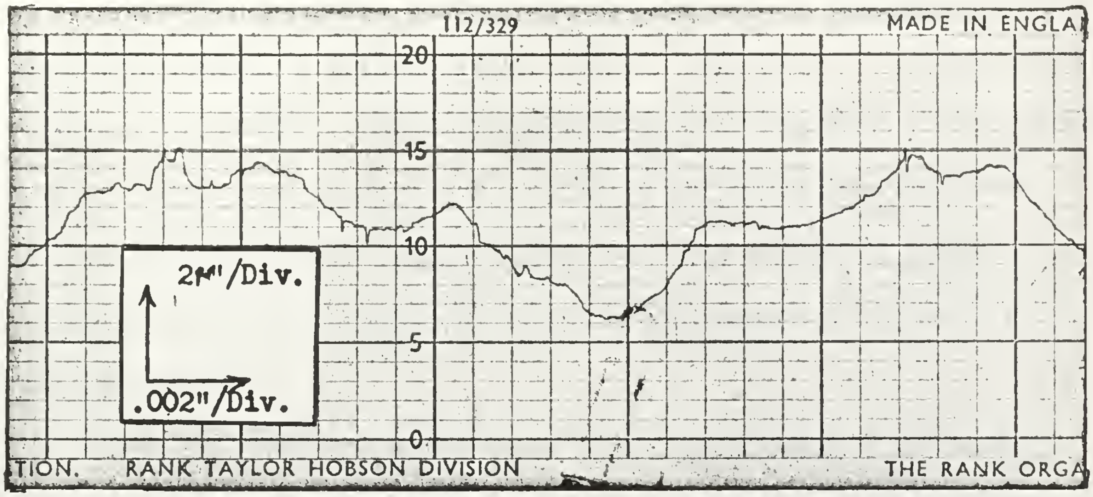


Figure 5. Circumferential surface finish.

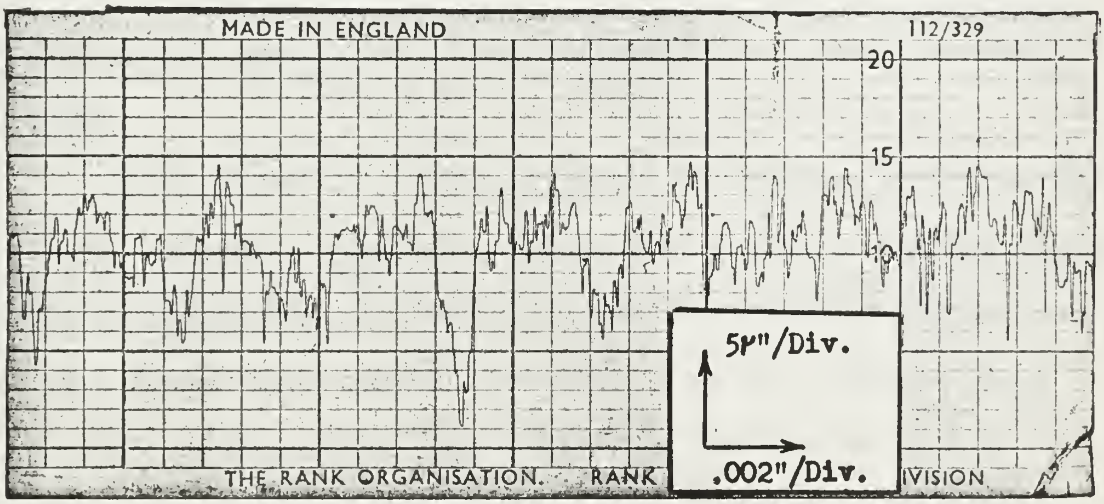


Figure 6. Axial surface finish.

The bearings used in the rotating portion of the unit are class "O" Timken tapered roller bearings with a guaranteed maximum radial run out of .00015". They are 3.000 inch bore bearings with a static radial load carrying capacity of 7800 lbs. These bearings were fitted to heavy steel hangers whose bore was carefully ground internally so as to contribute the minimum amount of eccentricity to the mounting.

That the bearings were better than the minimum specified by the manufacturer and a fine job of fitting up was accomplished, is borne out by the fact that the measured, assembled, unit radial run out at the test surface was .00015".

ILLUMINATION

Because the maximum gap illumination would provide the best signal to noise ratio at the small film thicknesses, several light sources were considered. These included both arc and incandescent types.

Of the former, the ordinary carbon arc provides a very intense light, but proved unsuitable because of its inherent arc instability. The zirconium-oxide arc (which is also known as a concentrated-arc lamp) showed great promise from both a size and brightness point of view. This, however, was regretfully abandoned when it was found that the power supply could not be filtered sufficiently to remove the "a-c" variation of the light.

Final recourse was made to the incandescent lamp in the form of an automobile headlamp bulb which gave constant illumination at reasonable intensity when powered by a storage battery.

This lamp was mounted in a shield with a collimating lens system as shown in Figure 7.

This permitted direction of the emergent light beam through the oil film and focusing lens onto the sensitive area of the photomultiplier tube. In addition the shield reduced greatly the amount of non-useful background illumination.

OPTICAL TRAIN

In order to obtain the light in its most useable form for measurements two sets of lenses were incorporated in the path of the light from source to detector. The first of these is mentioned above and serves to collimate the light beam. The light was then directed to the oil film through a 1/4 inch diameter passage 1 inch in length, which further enhanced collimation.

The light passing through the gap was collected and focused by an aerial photographic lens (Kodak Aero Ektar 7" F2.5). The diaphram adjustment of this lens also permitted further reduction of the unwanted light reaching the tube.

The light detecting device which is described in the section on instrumentation was an 1P-22 Photomultiplier Tube.

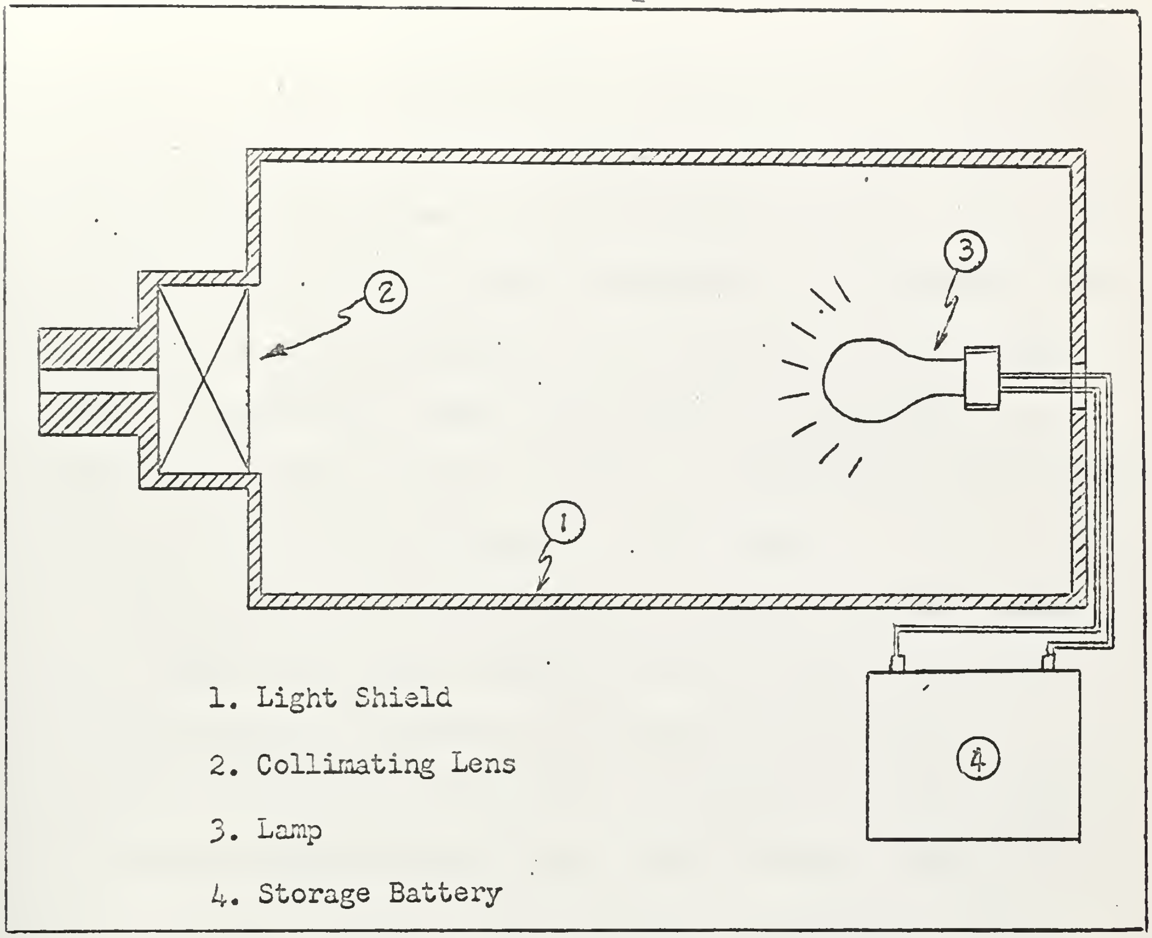


Figure 7. Schematic diagram of the light source.

3. INSTRUMENTATION

The purpose of instrumenting a system is to obtain engineering data from it, while introducing the minimum amount of interference with its operation. This must be done in such a manner that the maximum amount of information is gathered and converted, with minimum loss, into a form that may be interpreted. This requires that the measuring system incorporate units to perform the three functions of transduction, signal modification (or conversion) and presentation. Each of these functions, as they apply to the investigation at hand, will be discussed at some length.

The transducer, in the ideal case, should neither add noise to the signal, nor filter information from it. In the problem of determining film thickness-time behavior, the detection of variation in resistance, capacitance, inductance or light intensity are the most feasible methods among those available. Unfortunately all of the above, except a light intensity measurement, require precise rheological data on lubricants which is not available, and so are of questionable value. On this basis, the light intensity method was selected as the one most likely to yield effective measurements. An additional attractive feature of the method is that, out of all those available, it permits measurement with the least amount of energy removal from the measured system.

The method having been selected, the types of devices available were considered. They were:

a) Photo-voltaic devices

b) Photo-emmissive devices

The first of these gives a voltage output proportional to light intensity. They are also unfortunately non-linear with illuminated area and therefore unsuitable for use in this instance. The second type is a high impedance device operating by ionic conduction. The current flow through the device is proportional to the light intensity. The simplest of these is the photocell, having but a single set of elements and no gain. In the form of the photomultiplier this transducer has high gain, good frequency response, and is linear in operation. Its undesirable feature is inherent noise. The noise is a result of the high gain of the tube and the fact that the number of electrons released from the cathode per incident photon is statistical in nature. It is, however, possible to optimize the signal to noise ratio by adjustment of the biasing voltage. Because of its advantages, the photomultiplier tube was selected as the detecting element. Among those available, the 1P 22 type was deemed the most suitable. Its response curve, internal configuration and curcuit diagram are shown in Figures 8-10.

Modification of the output signal to remove the unwanted noise would seem to be desirable. Certainly any a-c modulation of the signal caused by an a-c component in the biasing supply voltage should be removed. As it turns out, the second modification is easy to accomplish; the first very difficult. A-C components of the supply voltage were filtered out by placing a 0.001 farad capacitor across the output of the power supply. While it appears that the same type of low pass filter might be applied to the signal output, it is found that effective filtration interferred

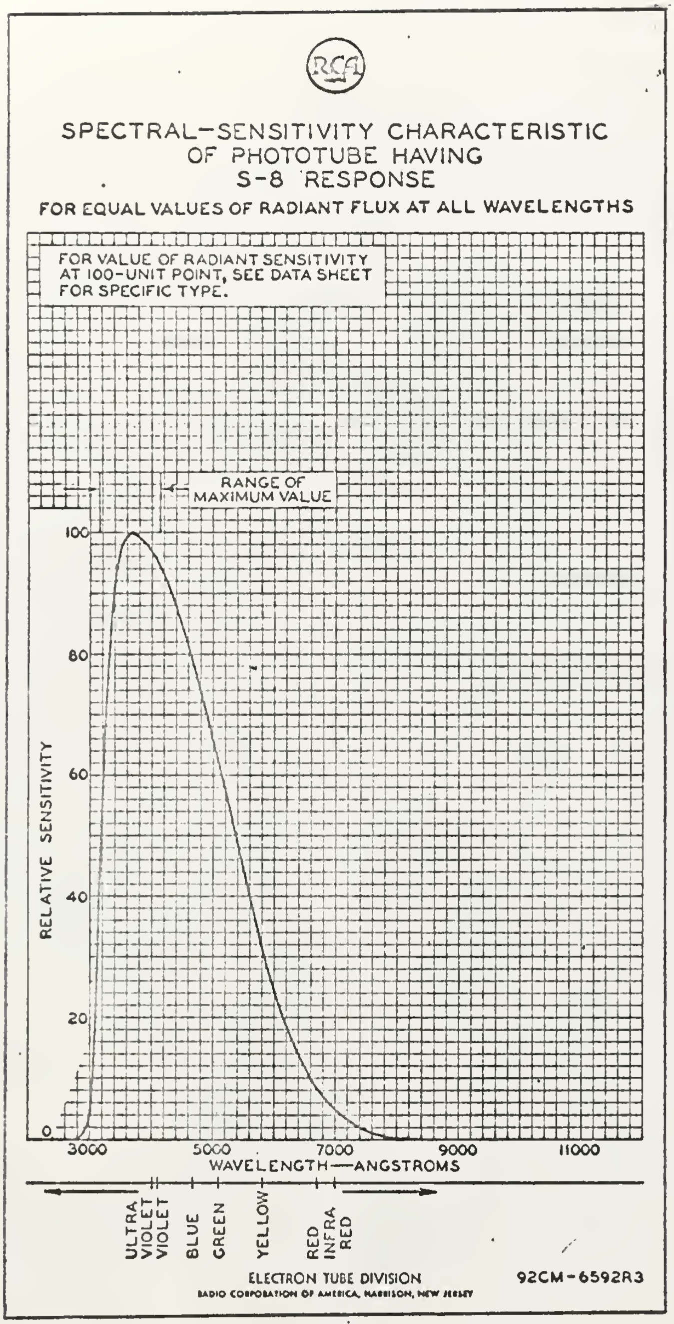


Figure 8. Spectral sensitivity of the 1P22

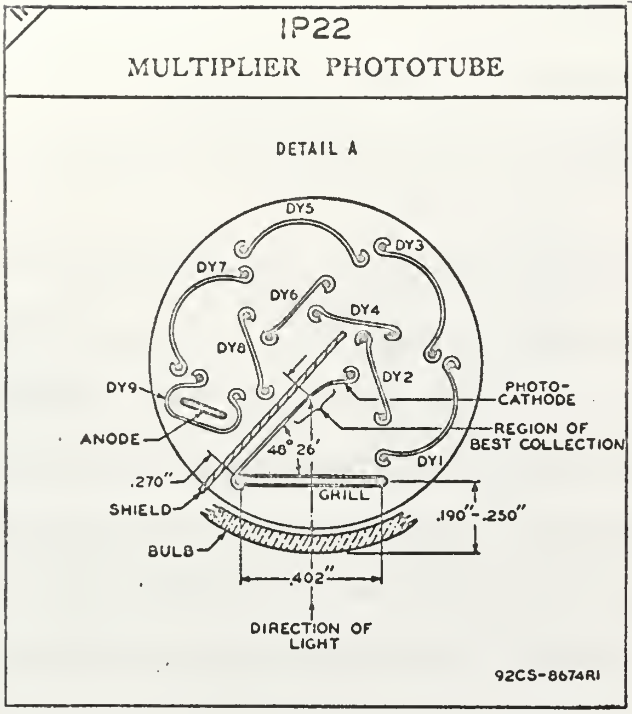


Figure 9. Internal configuration of the photomultiplier.

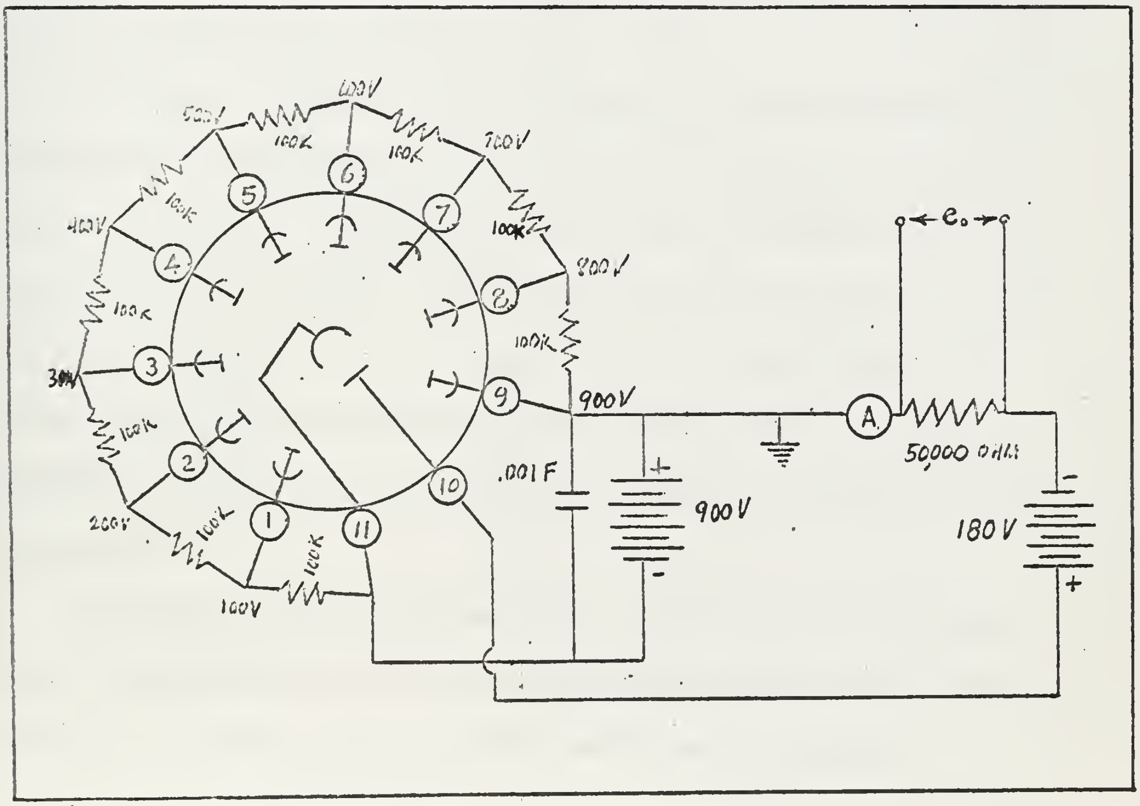


Figure 10. Photomultiplier circuit diagram.

with the system frequency response in the range of interest. For this reason it was decided to pursue the course of keeping the signal to noise ratio as high as possible, leaving the signal unfiltered.

Presentation of the data requires the variable amplification and frequency possessed only by the oscilloscope. Since the data is presented as a "one shot" high speed transient, the use of a conventional oscilloscope and oscilloscope camera posed recording difficulties. Although Polaroid film is available with writing speeds high enough to record almost any transient desired, exposure time determination and shutter syncronization are formidible problems.

These difficulties are neatly resolved, however, if an oscilloscope incorporating a trace storage feature is used. Experimental runs may be analyzed and photographed at the experimenter's leisure with the record of the transient continuously displayed on the scope face. Fixed shutter speeds may be used along with a slower, fine grain film. Such an oscilloscope was chosen for this project, in the form of the Hughes Aircraft Company Model 105 Memoscope. A Fairchild Dumont oscilloscope camera with Type 42 Panchromatic Polaroid film (ASA Speed index 200) was used for photo recording.

Frequency response problems were avoided as the transients under consideration were about a millisecond in duration, while the system bandwidth was from DC to well over a megacycle.

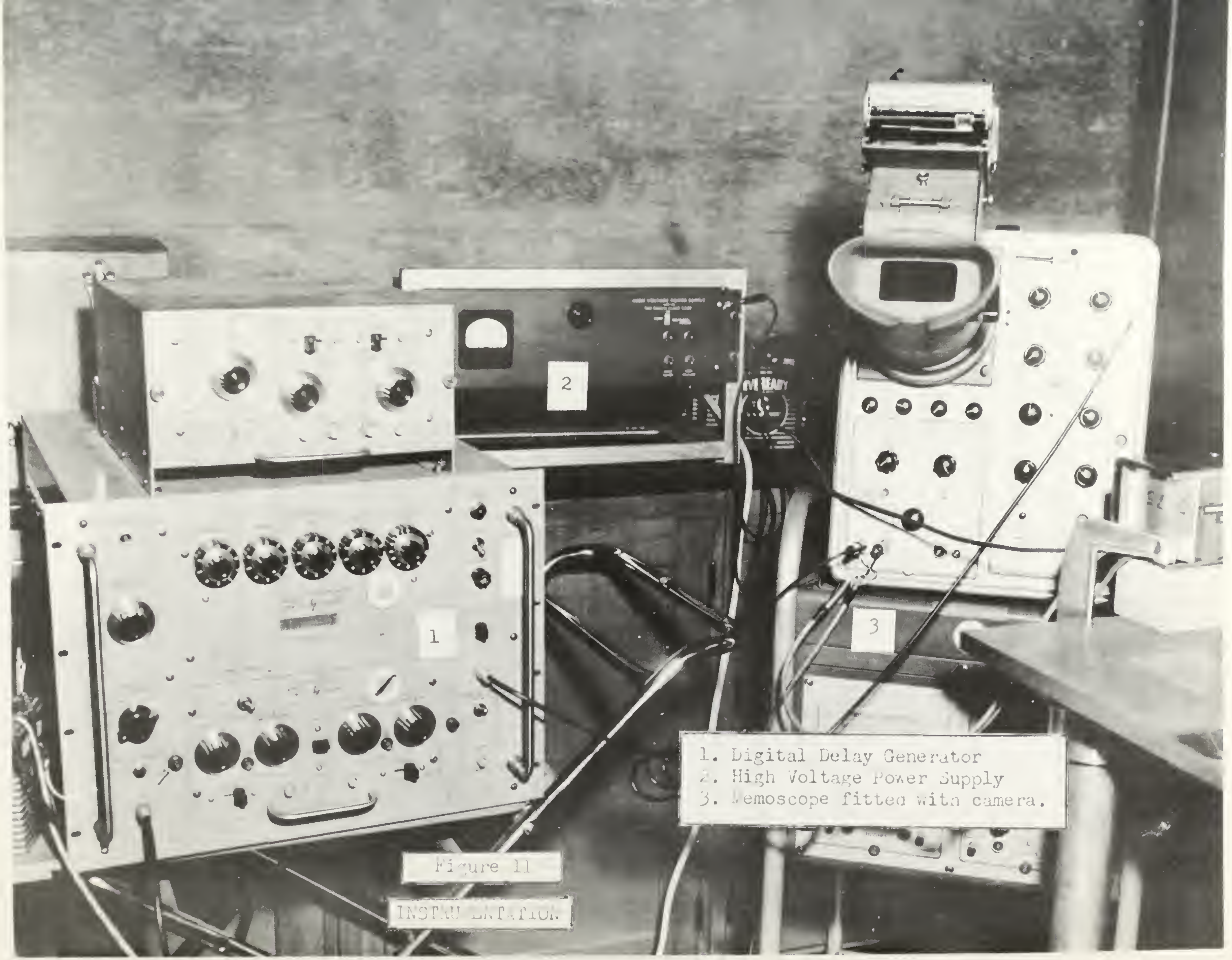


Figure 11

INSTRUMENTATION

4. EXPERIMENTAL PROCEDURE

Before discussing the actual measurement technique it is fitting that the operating considerations of the detector be examined. Those factors warranting detailed attention are felt to be:

1) optimum value of anode current
2) discrimination--the ability of the tube to reject extraneous inputs
3) optimum signal to noise ratio

High values of anode current have an adverse effect on both sensitivity and stability, and so are to be avoided. This is done by the proper selection of the tube operating load line and reduction of non-useful incident illumination. The last is rather straightforward and amounts to preventing as much background light as possible from reaching the tube. The optimum point here is when only the light to be measured reaches the detector. While virtually impossible to achieve, the approach in this experiment was as follows:

1) The unit was operated in a darkened room at night.
2) Non-reflective dark clothes were worn by the operator.
3) The light source was shielded.
4) The diaphragm of the focusing lens system was set to pass the light coming from the film but reject most reflections from the surroundings

Setting the zero reference equal to the operating point with zero input signal, calibrates out any remaining non-useful light.

Selecting the operating load line requires striking a balance. The slope and foot of the load line must be such that the tube operates in its linear range. They must also permit operation over the range of interest without drawing excessive anode current. In addition, since anode current provides the output signal (voltage drop across the load resistor) it must not be too small or a poor signal to noise ratio is obtained. For this tube, a 180 volt potential difference between the anode and dynode 9, with a 50,000 ohm load resistor, yielded the best results. This load line is shown on the manufacturer's curve of average anode characteristics in Figure 12.

The photomultiplier lacks discrimination. In addition to its inability to distinguish input signal from any other light striking it, the tube is influenced by magnetic and electro-static effects. To keep these from being incorporated in the output signal, the tube must be shielded. The 1P22 was mounted in a special housing for this purpose.

As previously mentioned, the normal operation of the detector introduces noise into the output signal. Furthermore, it was found that simple filtering could not be used to remove or effectively reduce this noise without impairment of the desired system frequency response. These two facts combined to make optimization of the signal to noise ratio highly desirable. It was pointed out in the discussion of optimum anode current that the situation is improved if the output current is as high as practicable, keeping in mind, of course, the difficulties involved. It is also possible to get

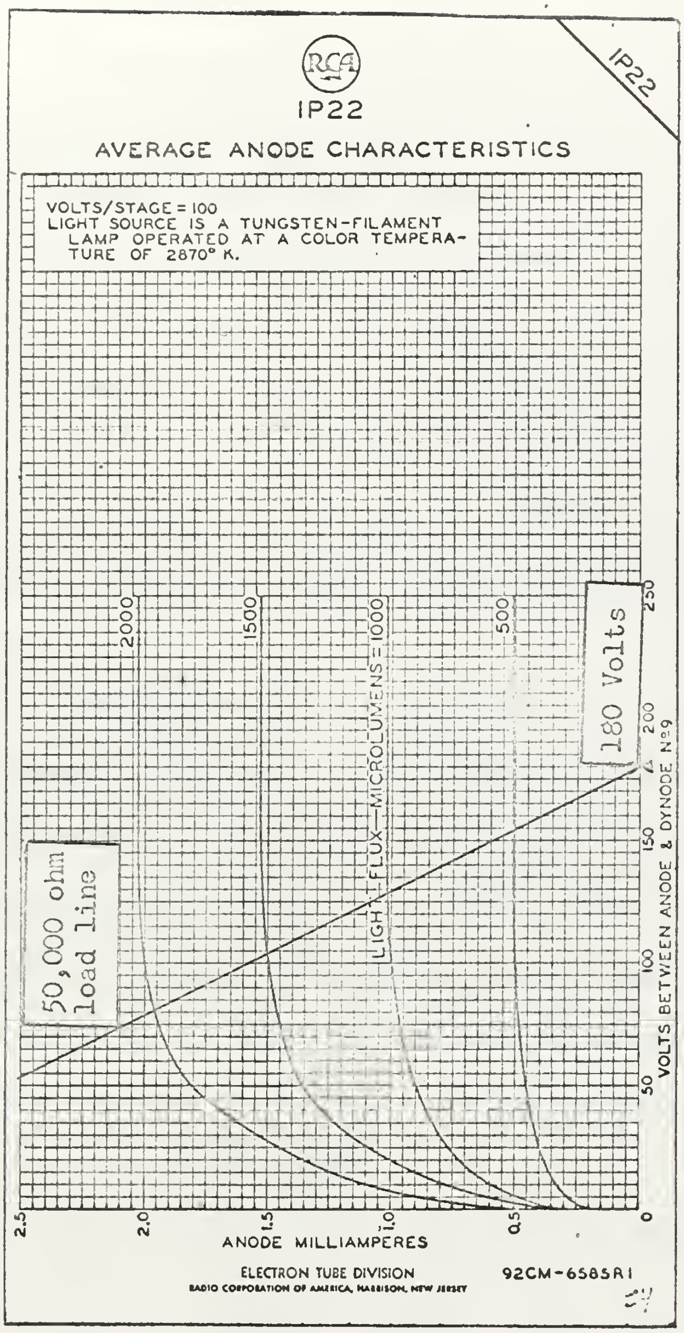


Figure 12. Average anode characteristics with operating load line.

at the heart of the difficulty, the amplification in the tube, by varying the voltage impressed across the stages from cathode to the last dynode. It was found that the optimum value for this voltage was 900V, or a potential difference between each stage of 100V. It is also probable that a small advantage might be gained by adjustment of inter-dynode voltages but this was felt to be negligible compared to the modification entailed. Figure 13 shows the sensitivity and amplification of the tube operated in this manner.

It is well, at this point, to consider two other factors which affect the quality of the output signal. Both introduce extraneous signal components.

The first of these are signals introduced into the system cable loops by magnetic induction. These signals may be reduced by a rather simple method. To see how this is accomplished it is advantageous to look at the origin of the induced signal. Maxwell's integral equation tells us that the electric field integrated around a closed path is equal to the negative time rate of change of the total magnetic flux enclosed by the path. Stated mathematically

$$\int_c \vec{E}\cdot d\vec{L} = -\frac{d\phi}{dt}$$

If the path is a wire curved upon itself with a gap between the ends

$$\int_c \vec{E}\cdot d\vec{L} = \int_{wire} \vec{E}\cdot d\vec{L} + \int_{gap} \vec{E}\cdot d\vec{L} = -\frac{d\phi}{dt}$$

because of the gap no current flows in the conductor and from Ohm's Law

$$E = RI = R(0) = 0$$

$$\int_{wire} \vec{E}\cdot d\vec{L} = 0$$

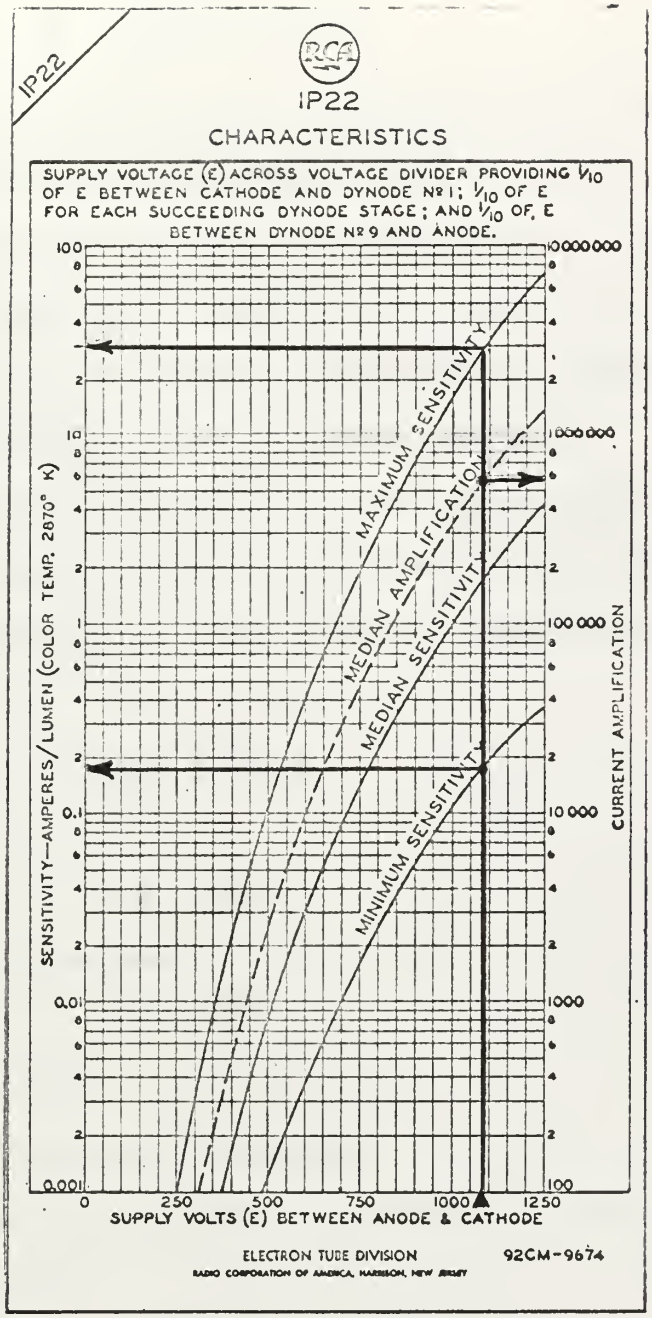


Figure 13. Photomultiplier sensitivity and amplification.

and therefore

$$-\frac{d\phi}{dt} = \int_{gap} \vec{E} \cdot \vec{dL} = V\ gap$$

In the case of a shielded lead, both the shield and the conductor inside have this induced voltage. Since no current flows in either the shield or the conductor the lead creates no magnetic field of its own. The trick, therefore, is to use the shield in a manner so as to create an opposing magnetic field, reducing the effect of the time varying flux on the inner conductor.

Returning to our wire we see that if we close the gap, current flows creating a field around the conductor with flux ϕ_c. The total flux is that from the source ϕ_s plus that contributed by the wire current.

$$\phi_t = \phi_s = \phi_c$$

and by definition

$$\phi_c = \mathcal{L}\, I$$

Since resistance R is defined

$$R = \frac{\rho L}{A}$$

where ρ is the resistivity

L is the length of the current path

A is the cross sectional area perpendicular to the current flow

Ohms law can be written

$$\frac{\vec{E} A}{\rho} = \vec{I}$$

integration around the loop gives

$$\int_c \frac{\vec{E}A}{\rho} \cdot \vec{dL} = \frac{A}{\rho} \int_c \vec{E} \cdot \vec{dL} = \int_c \vec{I} \cdot \vec{dL} = IL$$

$$\text{but} \quad \int_c \vec{E} \cdot \vec{dL} = -\frac{d\phi_t}{dt}$$

$$\text{so } I = \frac{A}{\rho L}\left(\frac{-d\phi_t}{dt}\right) = \frac{1}{R}\left(\frac{-d\phi_t}{dt}\right)$$

and therefore

$$\phi_t = \phi_s + \frac{\mathcal{L}}{R}\left(\frac{-d\phi_t}{dt}\right)$$

if ϕ_t is sinusoidal

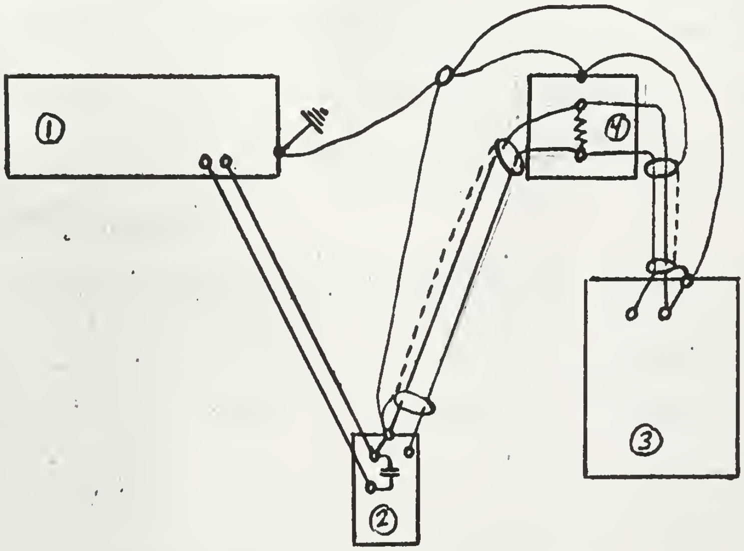
$$\frac{d\phi_t}{dt} = j\omega\phi_t$$

$$\phi_t = \frac{\phi_s}{1 + j\omega \mathcal{L}/R}$$

so the total flux is reduced by a factor of $1 + j\omega \frac{\mathcal{L}}{R}$

It is clear, therefore, that if the shield in the lead forms a current loop, the voltage induced in the inner conductor is reduced by a factor of $1 + \frac{j\omega\mathcal{L}}{R}$. Figure 14 shows how this applies to the instrument system used.

The second factor affecting the quality of the output signal is the aggravation of the magnetic induction problem and the addition of ohmic induction by multiple ground connections. If there are many connections to ground, additional loops for magnetic induction are formed. As a case in point, the oscilloscope, high voltage power supply and delay generator are all a-c operated and have a third grounding wire in the power cord. Were these all used, loops would be formed, inviting induction problems in the connecting leads. In addition this situation could result in the introduction of IR voltages into the loops as the ground is the sink for a variety of currents. This is simply another way of



1. High Voltage Power Supply

2. Photomultiplier

3. Oscilloscope

4. Tube Load Resistor

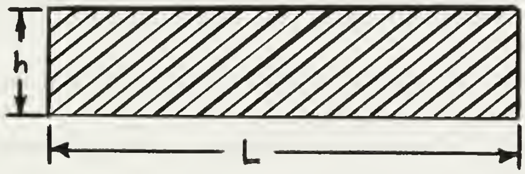
Figure 14. Shielding and ground connections.

saying the ground is "noisy" and it is not wise to include it as a circuit element. To avoid this problem and yet preserve the safety and reference level provided by grounding, a connection was made from each unit to the power supply and from it to the ground.

<u>CALIBRATION CURVE</u>

Next in order was the establishment of a calibration curve. This curve presents graphically the output signal corresponding to preset film thicknesses. This permited the evaluation of the output signal indicated on the oscilloscope in terms of gap width after the tests were made.

Since the detector measures only the amount of incident light, its output should be a linear function of the area through which the source illumination may pass. In a rectangle of length L and height h, as shown below,



the area varies linearly with h. If the photomultiplier is operating properly in its linear region, its output should be directly proportional to the value of h.

A problem is encountered in attempting to set precise, known, values of h into the unit. Various methods are available, but most entail an undue amount of complexity. The simplest, of course, is to set the gap with a spacer of known thickness, if it is possible

to insure consistant precise settings. This was found to be virtually impossible when the spacer had to be removed after the value of h was set. The difficulty was circumvented in the following way. Since the length L is much larger than the height h, the cross sectional area of a wire with diameter h is negligible with respect to the total gap area. Leaving a wire placed "end on" in the gap constitutes no appreciable reduction of gap illumination level but does eliminate the problem generated by spacer removal. Using measured wires, with care taken to avoid deformation while settings were made, allowed calibrated gap spacings to be precisely made.

In this experiment tungsten hot wire anemometer elements were used resulting in the calibration curve shown as Figure 15.

<u>EQUIPMENT SYNCHRONIZATION</u>

The goal in taking measurements was to obtain a trace on the oscilloscope which represented the time-thickness variation of the oil film. As the entire event takes place in a time span of the order of milliseconds, and happens only once, the single sweep of the scope trace must be synchronized to catch it. To do this a system triggering pulse must be introduced during the fall of the weight. The system must then delay an appropriate length of time before the sweep is started. The units used for this purpose merit some description.

System triggering was accomplished by a micro-switch activated by the body of the falling weight as shown in Figure 16. The location of this switch is important. Best results are obtained when it is placed as close to the impact point as possible. This

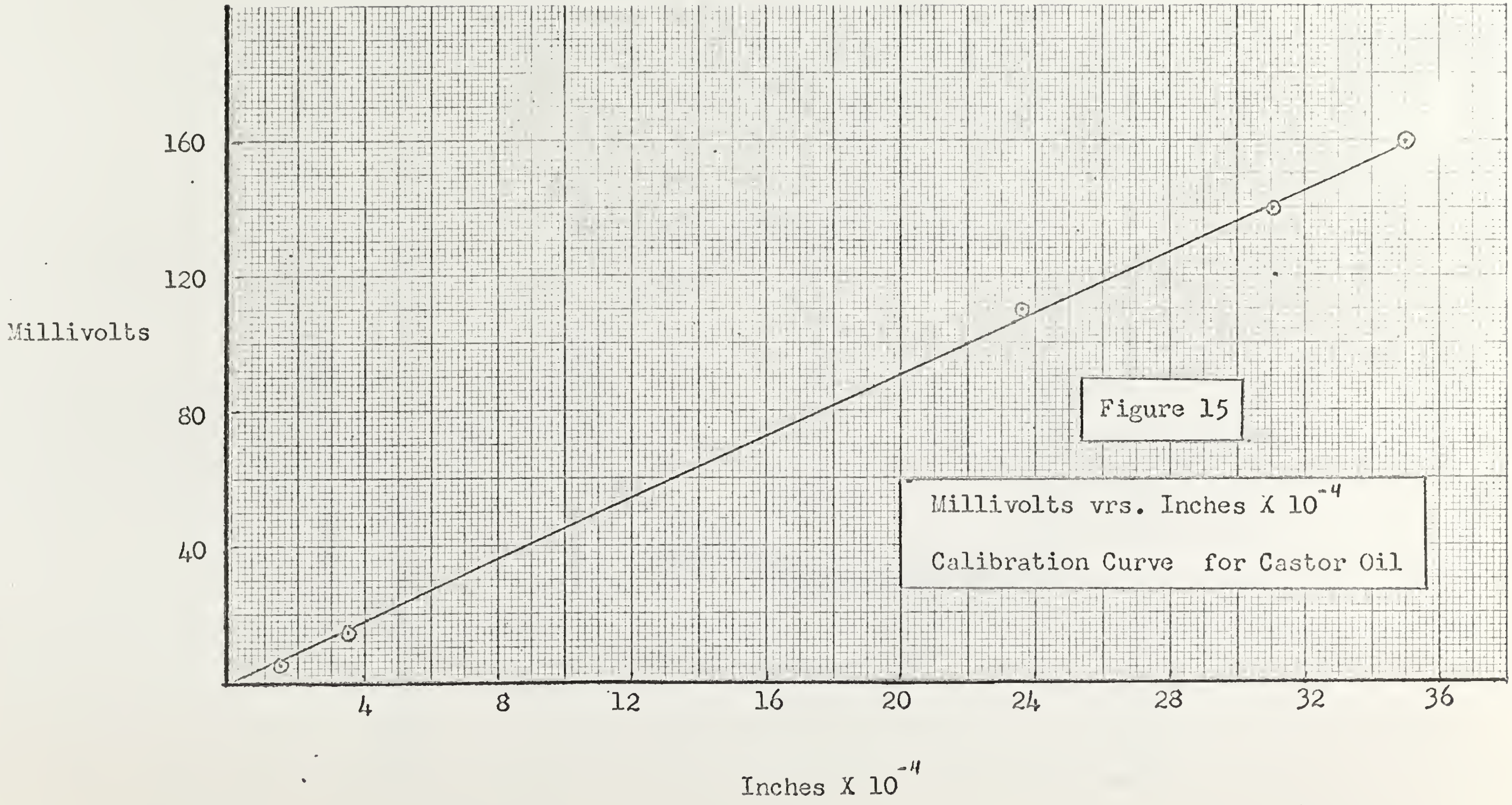


Figure 15

Millivolts vrs. Inches X 10^{-4}

Calibration Curve for Castor Oil

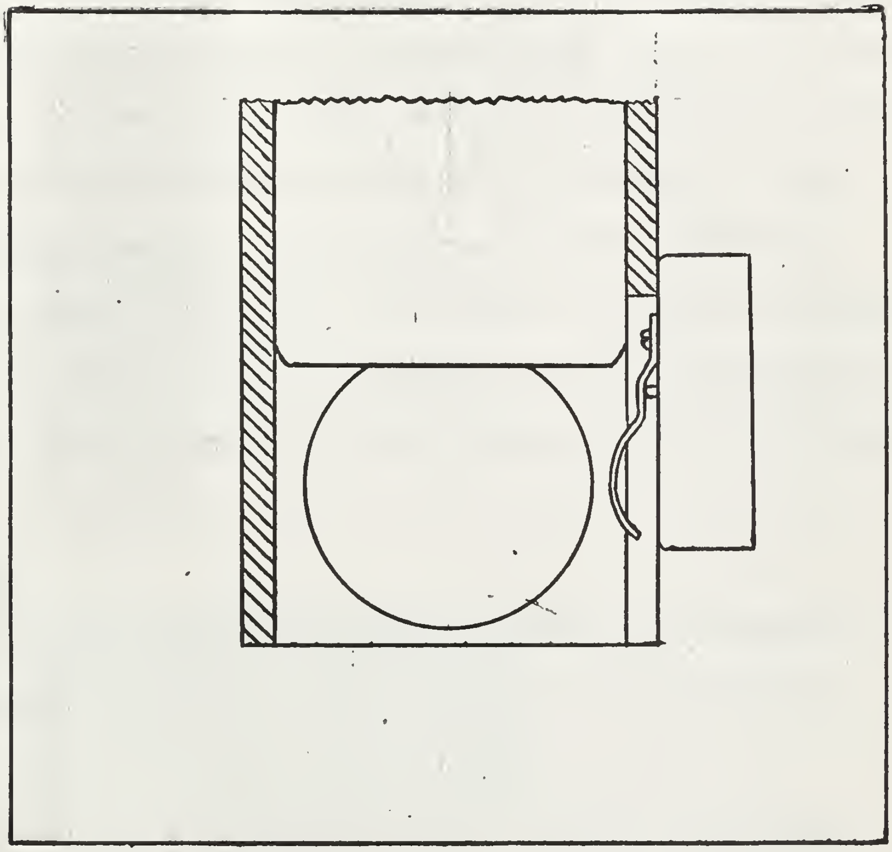


Figure 16. Delay triggering microswitch.

is so because the time of fall in various tests is not perfectly consistant, due to release phenomena and frictional effects. By minimizing the "metered" portion of the fall and selecting it to be at the terminal end, the time variation difficulties are eliminated. This short time between triggering and impact also permits the use of a very accurate delay generator to provide the necessary waiting period before triggering the oscilloscope trace. The Hewlett Packard unit used had a total delay capacity of 10,000 microseconds; the desired delay could be specified digitally between one microsecond and full capacity. After the preset interval this unit triggered the oscilloscope trace. The degree of precision afforded by this unit allowed the time represented by a full scope sweep to be shortened enough to present a clear picture of the time-thickness variation.

MEASUREMENTS

With the instrumentation at hand the taking of measurements was very straightforward. The steps followed, in chronological order are:

1) Weight positioned at desired height in drop tube
2) Lubricant applied to test surface
3) Zero reference established
4) Sweep armed
5) Weight electromagnetically released
6) Trace photographed

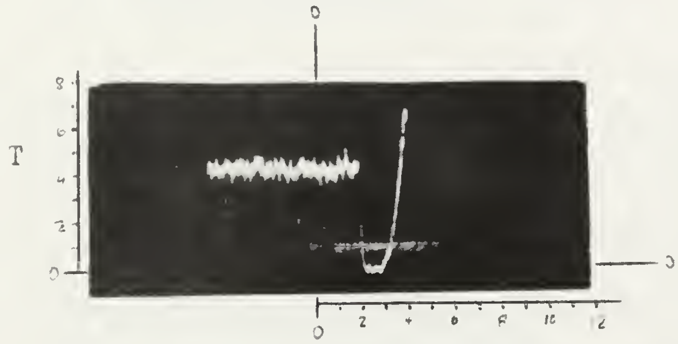
5. EXPERIMENTAL OBSERVATIONS

The experimental observations are, perhaps, best presented as commentary accompanying each photographic test record. It must be noted, in each case, that T is a normalized value of thickness. The true thickness is obtained by multiplying the normalized value by 4.4×10^{-4} inches.

STATIONARY UNIT TEST SERIES

TEST 1-1

Drop height- 13 inches



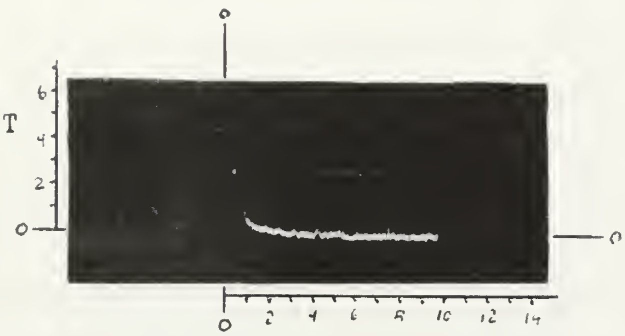
Time (milliseconds)

In this test the film thickness was initially 0.0019 inches. The trace displays a record of thickness reduction to a value which is not discernible from the zero reference. Very little, if any, deviation is indicated from the behavior expected of a Newtonian fluid. Note the chacteristic plateau

at the point of minimum film thickness. In this case, it is 0.001 second in duration. At the end of this period, elastic rebound of the members is indicated.

TEST 1-2

Drop height- 13 inches

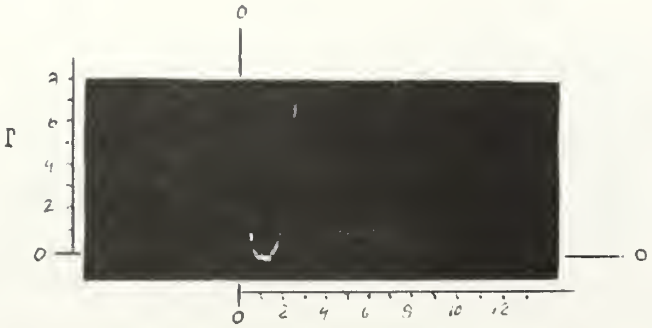


Time (milliseconds)

In this test, the film was initially thick enough to pass sufficient light to displace the trace from the face of the oscilloscope. The final value of the film thickness lies at the zero reference. Note the more pronounced curvature of the trace as the film thickness reaches a value of approximately 0.0001 inch. The lack of rebound indication is attributable to the failure of the drop weight to re-enter the guide tube properly.

TEST 2-1

Drop height- 19 inches

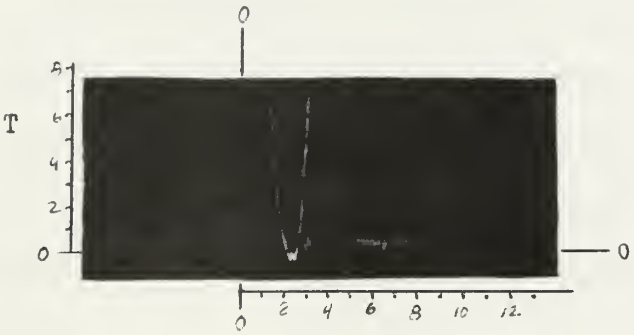


Time (milliseconds)

In this test, as in the previous one, the initial film thickness displaced the trace from the veiwing screen of the oscilloscope. Note the curvature of the trace as it approaches the zero reference. Prior to the test, both upper and lower film test surfaces were in contact with the oil and were wetted by it.

TEST 2-2

Drop height- 19 inches

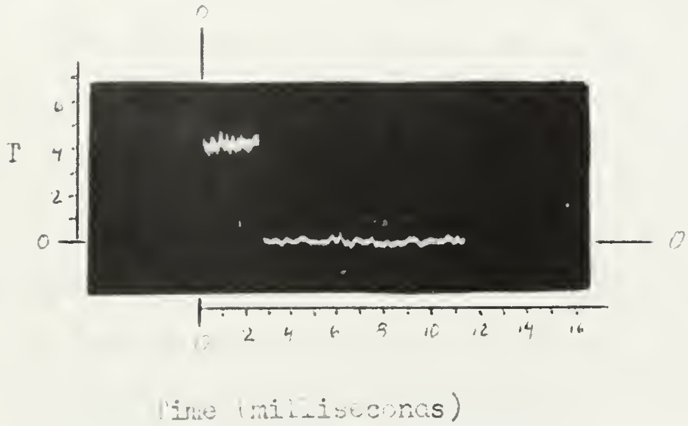


Time (milliseconds)

In this test, a thick film was applied to the lower surface. The upper surface, however, was not permitted to become wetted by the oil. Note the pronounced non-linearity of the leading edge of the trace. The final value of the film thickness lies at the zero reference.

TEST 2-3

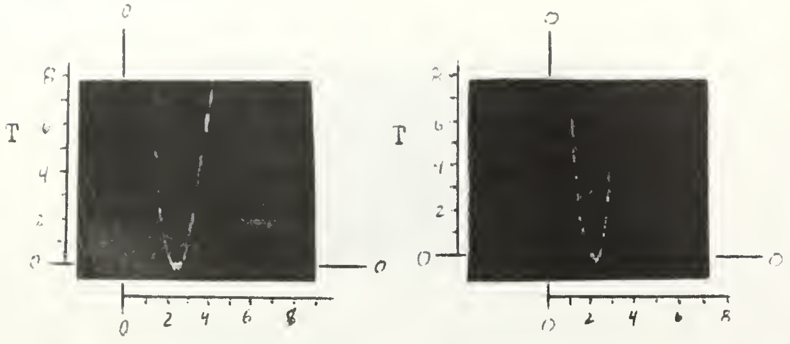
Drop height- 19 inches



To verify the findings of the previous tests, a thin film (0.0018 inches), was applied; both upper and lower surfaces being wetted. Note the return of the trace to that expected for a Newtonian fluid. The indicated lack of rebound is caused by the same effect explained in an earlier case.

TEST 2-4, 2-5

Drop height- 19 inches

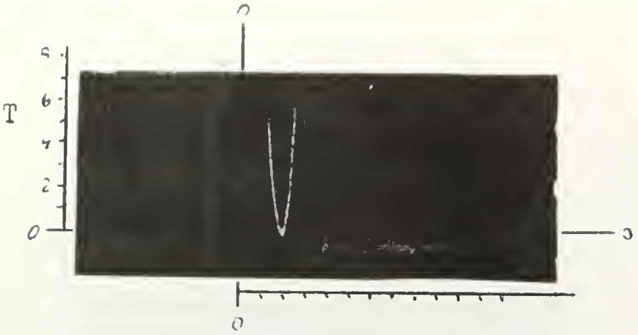


Time (milliseconds)

To determine the repeatability of the phenomenon, the procedure of testing with an unwetted upper surface and a thick film, was used twice again. Both traces display clearly the non-linear reduction of the film thickness. Note also the shortening of the time the system is static at the zero reference. The time in this case is about 0.0005 seconds, considerably less than when both surfaces were wetted. The two curves are almost identical to that obtained in test 2-2.

TEST 3-1

Drop height- 25 inches

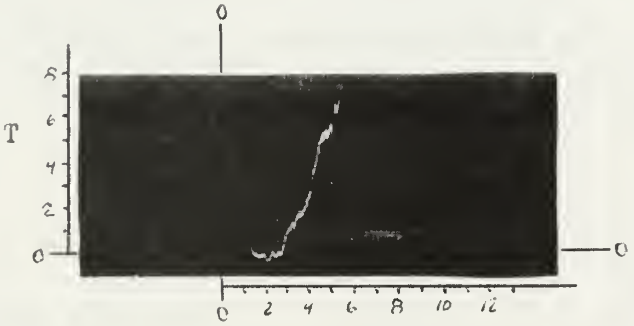


Time (milliseconds)

In this run, with increased drop height, the procedure using an unwetted upper surface and thick film again produced a trace showing non-linear behavior. The rebound is almost instantaneous.

TEST 3-2

Drop height- 25 inches

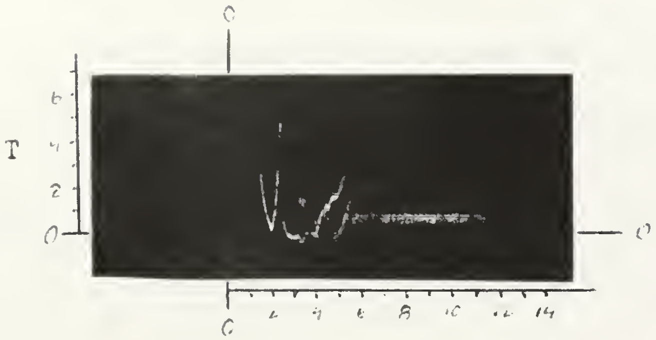


Time (milliseconds)

The test was repeated, again using a thick film, but with both surfaces wetted. A slight non-linear effect is noted in the last portion of the leading edge of the trace, at a value of film thickness of approximately 0.0005 inches. The plateau at the zero reference is about 0.0015 seconds.

TEST 4-1

Drop height- 43 inches

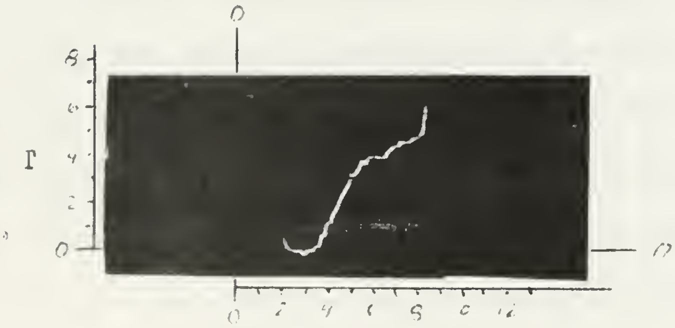


Time (milliseconds)

A thick film with the upper test surface not wetted was tested. The left hand trace in the photograph is the one under consideration. The right hand trace is a result of incomplete erasure of test 3-2. The superposition, while not intended, does permit side by side comparison of the two distinct types of traces obtained in this series of tests.

TEST 4-2

Drop height- 43 inches



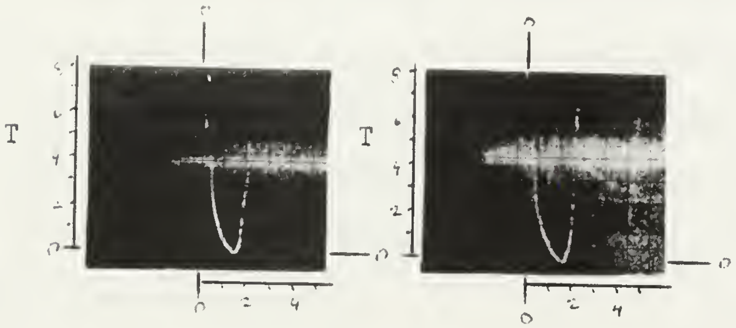
Time (milliseconds)

This test was performed to check the effects of this increase in drop height on the situation where we have a thick film with both surfaces wetted. The result shows the trace apparantly characteristic of this case. The zero reference plateau is about 0.0015 seconds in duration.

ROTATING UNIT TEST SERIES

TEST 1,2

Drop height-- 19 inches

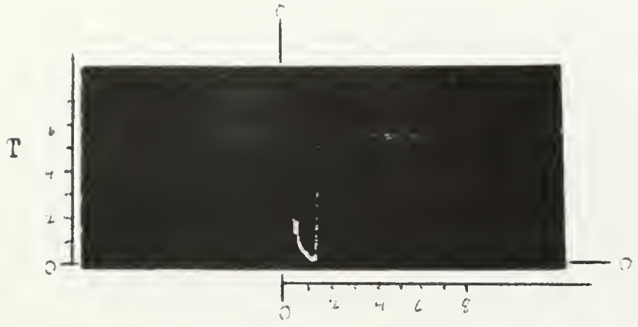


Time (milliseconds)

In these two tests the rotating member carried the oil film. The speed of rotation was 300 revolutions per minute. The purpose of the second test was to ascertain wether or not the result of the first was repeatable. In both tests the upper test surface was not in contact with the film prior to impact. The traces show clearly the similarity of the results, and the non-linear variation of film thickness.

TEST 3

Drop height- 19 inches

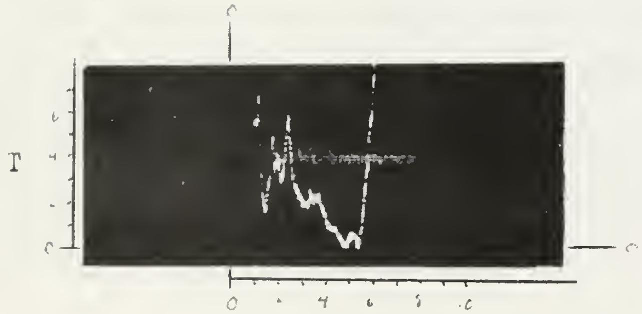


Time (milliseconds)

In this test, a small amount of lubricant was added to the upper test surface in the form of a suspended droplet at the contact point. Prior to impact, neither the upper surface nor the oil droplet were in contact with the rotating film. Note the indication of a retrace on the leading edge of the curve.

TEST 4

Drop height- 19 inches

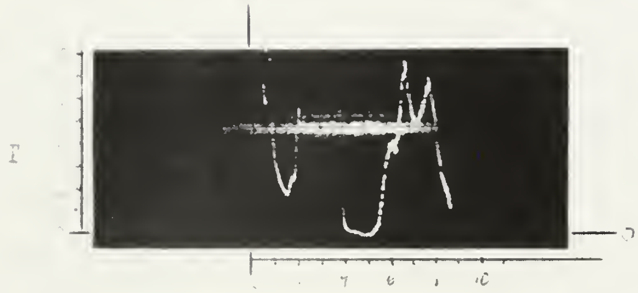


Time (milliseconds)

In order that this effect might be better observed, the maximum amount of oil that could be suspended from the upper surface was applied. In this photorecord, the complex behavior indicated, but not clearly discernible in test 3, is shown in detail. Note the rebound indicated before the zero reference is reached; strongly suggesting an elastic reaction between the lubricant and the upper test surface.

TEST 5

Drop height- 1½ inches

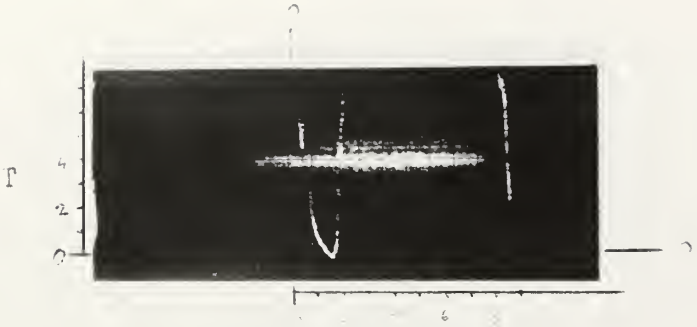


Time (milliseconds)

In this test, the oil on the upper surface was allowed to touch the rotating film. Again the double rebound effect is evident. The general shape of the trace is considerably different from the previous test. The plateau characteristic of the wetted non rotating case reappears here on the second rebound.

TEST 6

Drop height- 19 inches

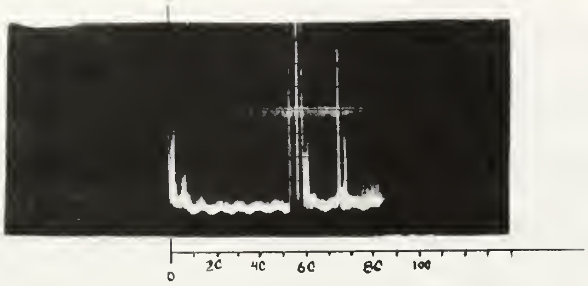


Time (milliseconds)

In this test the rotating speed was increased to 570 revolutions per minute. No oil was present on the upper surface, and it was not in contact with the film prior to impact. The trace obtained is very similar to those obtained in tests 1 and 2.

TEST 7

Drop height- 19 inches



Time (milliseconds)

The oscilloscope photograph above shows the type of trace obtained in a test performed with no lubricant on the test surfaces. It is presented for comparison purposes. Since there is no film thickness involved, the ordinate is omitted. Note the absence of the slope changes indicated in the lubricated cases.

6. DISCUSSION OF RESULTS

The results of the tests can be summarized as follows:

1. Impact loading of an oil film causes a non-linear thickness-time behavior.
2. The non-linearity varied in degree, depending on the initial conditions. In general, surface wetting films, initially less than 0.010 inches thick, give very little indication of surface approach velocity change. This is not to say that it does not occur, but rather that it is difficult to establish that it does from these results. A distinct change was noted if the initial film was greater than 0.030 inches thick.
3. The change in approach velocity does not become evident until the film thickness is reduced by the impact to about .0005 inches.
4. Tests conducted with both surfaces wetted show a characteristic delay, at minimum film thickness, before rebound. The length of this delay was virtually unaffected by the magnitude of the impact.
5. A marked difference in the result was indicated if the upper test surface was not wet prior to the impact. This difference manifested itself as an increase in non-linearity and a reduced delay before rebound.
6. As the magnitude of the impact is increased, in the non-wetted case, the delay disappears completely.

7. The same type of behavior is seen in the tests with relative motion between the surfaces. The principle differences are: a) increased non-linearity and b) evidence suggesting an elastic behavior of the film under certain test conditions.

8. It was not possible in the test results, in general, to distinguish the minimum film thickness from the zero reference.

The non-linear behavior evident in these results seems to indicate that interactions in the film restrict the movement of the lubricant from the point of contact, causing it to resist the squeezing action in a manner akin to that of a plastic solid.

That the effect is much more pronounced in the non-wetted case is probably due to the fact that egress is somewhat easier over wetted surfaces. The finite time required to wet the upper surface; keeping in mind the short time required for the entire squeezing of the film, further slows down movement, enhancing the resistive effort. The non-delayed rebound found with the larger impacts hints at the possibility of elastic action in the film.

In the cases where the lower test surface was rotating the non-linearity was more pronounced, but the behavior was similar in nature to that cited for the previous case. The most significant effect came to light when lubricant was added to the upper test surface prior to impact. A double rebound became apparent. The first occurred at a point within the film, before the minimum thickness

was reached. The second rebound bore a marked similarity to the stationary tests in that there was a delay when the lubricant on the upper and lower surfaces was in contact prior to impact. Without this contact there was no delay. This behavior is strongly indicative of an elastic reaction in the film.

Three explanations are considered for the fact that the final film thickness was not discernable as a non-zero value. They are:

1. The film was reduced to a thickness which permitted sufficient asperity contact to attenuate the light passing through to essentially zero.
2. Asperity contact occurred on the periphery of a pocket of lubricant entrapped between the elastically deformed surfaces.
3. The attenuation is such as to require additional signal to noise ratio optimization, for detection of extremely small quantities of light.

The first two explanations hypothesized, represent physical limitations on the method. The third and most probable explanation, fortunately, encompasses an area in which improvements can be made. Suggestions are detailed in the material included in the next section.

7. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

It can be concluded that the experimental technique provides a practical means of studying the thickness-time variation of lubricant film under suddenly applied loads, and should prove to be a useful research tool.

In addition, the test results provide an insight into a little known area of lubricant behavior. From them the following conclusions may be drawn:

1. Under short duration-high intensity loading the lubricant film displays the ability to resist deformation in a non-linear manner similar to that of a plastic solid.
2. Under the same type of loading it is possible for the lubricant to display properties attributed to an elastic solid as well.
3. It is reasonable to postulate that these effects manifest themselves in the operation of machine elements, and play an important part in the mechanism of lubrication.

RECOMMENDATIONS

It is most strongly recommended that this work be continued. Experiments to explore the effects shown by other lubricants, higher rotative speeds, etc., can be carried out with no changes to the existing test unit. Minor changes to the mechanical portion would permit film loading measurements. Further enhancement of the signal to noise ratio of the detection system would permit a renewed attack on the problem of determining the final film thickness.

Since information on the final film thickness would be extremely useful and its determination provides a logical extension to this work, several promising modifications to the detection system merit consideration.

As mentioned previously, increased amplifier gain is not the answer in an effort to extend the system response to extremely low levels of illumination. The noise generated by the detector is amplified as well as the signal and the situation is not improved in any way. Filtration to remove the noise is impractical because its period is one order of magnitude larger than the duration of the event under observation.

One solution is to raise the level of the illumination reaching the detector by increasing the intensity of the source. The requirement for illumination stability places restrictions on the source selection which unfortunately renders unsuitable many of the high intensity types. One such intense source, the 500 Watt "Point O Lite" shows promise if its power supply can be suitably filtered.

Another approach has its foundation in the spectral sensitivity characteristics of the tube. While stability and intensity requirements favored the incandescent lamp it must be noted that the maximum tube sensitivity occurs in a region of the spectrum which lies between 3150 and 4150 angstroms. An energy distribution curve plotted for an incandescent lamp shows that only a small portion of its energy is emmitted with wavelength in this region. It is seen therefore than an intense source with required output stability tending more toward the ultraviolet would be an ideal

choice. Such a source, unfortunately, is not readily available. It is felt, however, that the hydrogen arc merits consideration in this respect.

It is apparent that the method and the unit provide an effective means of extending the knowledge in this field, and should be given considerable attention.

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APPENDIX A

EQUIPMENT LIST

Oscilloscope	Model 105 MEMOSCOPE Oscilloscope Serial number 50341 with Model 05-3 High Gain Preamplifier, both manufactured by the Hughes Aircraft Company.
Delay Generator	Model 218A DIGITAL DELAY GENERATOR manufactured by Hewlett Packard.
Power Supply	Model 710-PR Regulated High Voltage Power Supply Serial number 3118 manufactured by Furst Electronics.
Photomultiplier	1P-22 Photomultiplier Tube manufactured by RCA.
Light Source	21 Candlepower Headlamp Bulb Type number 1129 manufactured by Edison Mazda.
Camera	Oscillograph Camera Model 297 Serial number 5A56 manufactured by Fairchild Dumont.